Dynamical Climatology

Comparison of data and derived quantities for the middle atmosphere of the southern hemisphere

by

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COMPARISON OF DATA AND DERIVED QUANTITIES FOR THE MIDDLE ATMOSPHERE OF THE SOUTHERN HEMISPHERE

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ABSTRACT

Before data from satellites can be used with confidence in dynamical studies of the middle atmosphere an assessment of their reliability is necessary. To this end, independently analysed data from different instruments may be compared. In this paper, this is done for the southern hemisphere as a prelude to the dynamical studies of the middle atmosphere being fostered by the MASH project of the Middle Atmosphere Program. Data from two infrared radiometers are used: a limb scanner (LIMS) and a nadir sounder (SSU). While there is usually qualitative agreement between basic fields (temperatures, winds), substantial quantitative differences are found, with more pronounced differences in fields of Eliassen-Palm flux divergence and Ertel's potential vorticity.

The fidelity of the base-level analysis to which satellite data are tied is important for calculating quantities of relevance to dynamical theory. In the southern hemisphere, conventional data are sparse and, through the analysis procedure, this introduces errors into derived fields for the middle atmosphere. The impact of using base-level analyses from different sources is assessed. Large discrepancies are found in fields computed by differentiation.

Several techniques are suggested whereby the reliability of fields derived from satellite data may be gauged.

1. INTRODUCTION

For over 15 years, near global measurements of temperature and constituents obtained from satellites have provided information on the

thermal structure and distribution of trace species in the middle atmosphere. From these data, it has been possible to infer quantities useful in studies of dynamical and transport processes in the middle atmosphere (e.g. winds, potential vorticity, fluxes of trace chemicals). Data are available for different time periods from several instruments, each with differing spatial coverage and resolution. Before such data can be used with confidence in dynamical studies, an assessment of their reliability is necessary, an indication of which can be obtained from a comparison of data from different sources, e.g. different radiometers on board satellites in independent orbit. As part of the MAP PMP-1 project*, a number of such exercises have been completed for the northern hemisphere (Rodgers, Ed., 1984; Grose and Rodgers, Eds,. 1986). For example, a comparison was made of basic temperature data and derived quantities from the following instruments: the Limb Infrared Monitor of the Stratosphere (LIMS); the Stratospheric and Mesospheric Sounder (SAMS); and the Stratospheric Sounding Unit (SSU).

These studies concentrated on the northern hemisphere for two reasons. First, the availability of conventional (rocketsonde, radiosonde and balloon) data for comparison with the satellite data was much greater than for the southern hemisphere, where conventional data are sparse. Secondly, winter in the northern hemisphere is more dynamically active, with striking phenomena such as major mid-winter warmings, and hence has attracted more interest. It is now being increasingly realised, however, that the middle atmosphere of the southern hemisphere, despite the absence of major mid-winter warmings, is far from quiescent. Very intense, dynamically induced warmings occur in late winter; the intense polar night vortex may be the seat of instabilities which may affect the circulation on a large scale; and travelling waves can,

*Middle Atmosphere Program Pre-MAP Project 1

on occasions, be clearly seen in the more zonally symmetric circulation of the southern hemisphere.

The marked differences in the circulation of the two hemispheres afford atmospheric scientists the opportunity to study what are, in some respects, two different atmospheres. The elucidation of dynamical mechanisms and transport processes is bound to be furthered by comparison.

Under the auspices of the Middle Atmosphere Program, the MASH project (Middle Atmosphere of the Southern Hemisphere) was initiated to act as a focus for a concerted study of the dynamics and transport in the middle atmosphere of the southern hemisphere. An integral part of this project is a comparison of data from different sources, along the lines of that done for the northern hemisphere. To this end, an international workshop - involving scientists from Australia, Federal Republic of Germany, Japan, U.K. and U.S.A. - was held in Williamsburg, Virginia in April 1986. In addition to the comparison of satellite data, an important aim of this workshop was to assess the impact of using upper tropospheric analyses from various sources as base levels. (A base level analysis of geopotential height, typically at 100 mbt, is used with the hydrostatic approximation to construct analyses at higher levels.) This is a particularly important exercise for the southern hemisphere because of the paucity there of conventional measurements in the troposphere.

A comprehensive report on the proceedings of this workshop is in preparation (O'Neill and Grose, Eds.). It is beyond the scope of the present paper to address all of the issues considered and conclusions reached by the many scientists who participated in the workshop. Instead, we have selected a

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†The pressure unit is taken as the mb. The equivalent S.I. unit is the hPa.

few illustrative examples for this summary to serve as prelude to investigations that will be fostered by the MASH project. We shall restrict attention here to data from two instruments with different viewing geometries: a limb scanner (LIMS) and a nadir sounder (SSU).

In section 2, we briefly describe the data sources. In section 3, we present some examples of the comparisons of data and derived quantities which typify those made in the workshop. Differences between the various base-level analyses, and the resulting impact on derived quantities, are discussed in section 4. Finally, we list our conclusions in section 5 and give recommendations which may be helpful in future studies of dynamics and transport in the middle atmosphere of the southern hemisphere.

2. DESCRIPTION OF DATA SOURCES

In this section, we give brief descriptions of the LIMS and SSU instruments used in this study, and of the methods by which gridded fields were constructed. We list the base-level analyses used, and note the time periods for which the comparisons were made.

2.1 Satellite data and method of analysis

LIMS is a limb-scanning, infrared radiometer (Gille and Russell, 1984). Radiation emitted by the 15 micron bands of carbon dioxide is measured in two spectral channels. Temperature is then inferred from the radiances using an iterative retrieval scheme (Gordley and Russell, 1981). Synoptic temperature fields at 12 GMT are produced using a Kalman filter technique (Haggard et al., 1986). The spatial resolution of gridded fields derived from

the instrument is about 3-5 km in the vertical, 4° in latitude, and wavenumber 6 in the zonal direction. Useful data cover the period 25 October 1978 to 28 May 1979, with a latitude range 84°N to 64°S, and an altitude range 15 to 70 km. Fields of geopotential height are constructed from temperature fields using a geopotential-height analysis at 50 mb provided by the U S National Meteorological Center (NMC).

SSU is a nadir-viewing, pressure-modulated, infrared radiometer which scans both sides of the sub-orbital track (Pick and Brownscombe, 1981). The SSU instrument is part of the TIROS Operational Vertical Sounder (TOVS) system. For the period of the LIMS/SSU comparison (May 1979 in this paper), radiances are available only from two out of three channels of an SSU - those peaking at 15 and 5 mb. For the period used to assess the impact of different base levels, information from a channel peaking at 1.5 mb is also available, together with radiances from another two radiometers: a microwave sounding unit (MSU) and a high resolution infrared sounder (HIRS-2), most of whose channels peak in the lower stratosphere.

Independent retrievals of the data are carried out by the U K Meteorological Office (UKMO) and by NMC. Only the former are used in the present study; at the Williamsburg workshop both data sets were used for comparison with each other and with data from other satellites.

In the UKMO analysis, radiances are inverted by statistical regression (using a reference climatology) to give daily fields of thickness at 12 GMT. For the period of the LIMS/SSU comparison, the regression coefficients do not vary with latitude or season, though they do thereafter. Geopotential heights are obtained by adding the thicknesses to a base-level analysis of geopotential height at 100 mb obtained (for LIMS/SSU comparison) from NMC. Temperatures are computed by differentiating these heights in the vertical.

The spatial resolution of the gridded fields is about 12 km in the vertical, and wavenumber 12 in the meridional (pole-to-pole) and zonal directions. Useful data cover the period from October 1978 to the present, with a latitudinal range from 87°N to 87°S and an altitude range from about 15 to 50 km. Further details of the data analysis and a discussion of the errors involved are given by Clough et al. (1985).

2.2 Base levels

To assess the impact of using different base levels on derived quantities in the stratosphere, analyses of geopotential height at 100 mb were obtained from archived products at three meteorological centres: UKMO, NMC and the European Centre for Medium Range Weather Forecasts (ECMWF). It is beyond our scope to describe the procedures adopted in producing these analyses (and we are in no position to judge their relative merits). Details can be obtained from the centres concerned.

2.3 Time periods for comparison of data

A constraint dictating the time periods for the comparison of the basic satellite data was the short record (7 months) of LIMS data that is available. At the Williamsburg workshop, comparisons were made for the months of January and May 1979. May is the more dynamically active month, so we expect a higher signal-to-noise ratio then. We shall restrict attention here to the results for a few days in May; they were chosen to be representative of the month.

To examine the effect of the different base-level analyses on derived

quantities, UKMO analyses of thickness for September 1985, also a dynamically active month, were added to the base levels from the three sources. Again, results shown (for two days) are representative of the month.

3. RESULTS

3.1 Zonal-mean temperatures

Latitude-height sections of zonal-mean temperature, derived from SSU and LIMS measurements, are shown on 19 May 1979 in Fig. 1. (Being based on thicknesses, SSU temperatures are layer means.) Although the fields are in broad agreement, there are significant differences, particularly in the upper stratosphere where SSU temperatures are about 10-15 K colder than those from LIMS, and vertical temperature gradients are correspondingly smaller. In the middle and lower stratosphere, differences between the two fields are smaller, about 3 K, with SSU temperatures generally colder. Similar differences are present on other days in May (and in monthly-mean fields).

On the satellite TIROS-N, which provided data for analyses until June 1979, the top channel of the SSU radiometer (weighting function peaking near 1.5 mb) was inoperative, and HIRS and MSU radiometers were not carried. The vertical resolution of derived fields was impaired, and this must contribute to the above differences in temperature.

3.2 Zonal-mean winds

Corresponding cross-sections of zonal-mean geostrophic wind are shown in Fig. 2. The two fields show good agreement in the position of the maximum of

the westerly jet (near 50°S at 1 mb), and weak easterly winds are present in both at 20°S in the lower stratosphere. The largest differences, of up to 12 m s^{-1}, are near 20°S at all altitudes. Differences are smaller at mid latitudes (3 m s^{-1} or less at 60°S). There is no consistent pattern in the differences between the two wind fields from one day to the next, except that, in May 1979, vertical shears tend to be greater in wind fields derived from LIMS than in those from the SSU on TIROS-N (probably because of the missing top channel on this SSU).

3.3 Eliassen-Palm fluxes

Cross-sections, from LIMS and SSU data, of the (quasi-geostrophic) Eliassen-Palm flux divergence in the southern hemisphere on 19 May 1979 are shown in Fig.3 (a scaled form of this quantity is actually plotted as explained in the caption). In the stratosphere, the two terms that constitute this divergence (see Eq. 2.2 in Dunkerton et al., 1981) are frequently large and of opposite sign, so the divergence is prone to large errors. Indeed, on the day shown, there is no apparent qualitative, let alone quantitative, agreement between the two fields. The LIMS field has convergence over a broad latitudinal band at middle latitudes, whereas the SSU field has divergence. It is likely that the SSU field is the more suspect of the two, for it shows little continuity from one day to the next around the chosen day; the continuity of the LIMS field is better.

The serious discrepancies noted here between fields of E-P flux divergence are probably attributable to the poorer than normal vertical resolution of the SSU analyses in the first half of 1979. Afterwards, SSU analyses should generally be of much better quality (as found by Grose and

Rodgers, 1986), because of better instrument performance and additional data from the HIRS-2 and MSU radiometers. Even so, the vertical resolution of the best possible analyses from these instruments is poorer than that from LIMS. As most of the longitudinal variance in the stratosphere is in the longest zonal waves, which LIMS analyses should be able to resolve, side-scanning in the SSU instrument does not prove to be a significant advantage for the calculation of E-P flux divergence, but it can be for calculations of synoptic maps of potential vorticity.

3.4 Isentropic maps of Ertel's potential vorticity

Fields of Ertel's potential vorticity, Q, shown here are calculated using the following approximate expression:

$$Q \approx -g(\zeta+f)\partial\theta/\partial p$$

where ζ is the relative vorticity, f the Coriolis parameter, θ potential temperature and p pressure. It is a highly differentiated quantity: basic fields must be differentiated to obtain approximate values for the horizontal wind components (using the geostrophic approximation), and then the winds must be differentiated to obtain relative vorticity. Errors in Q are thus liable to be large. In view of their potential value to studies of dynamics and transport (McIntyre and Palmer, 1983, 1984 and 1985; Hoskins et al., 1985; Miles and Grose, 1986), the reliability of isentropic maps of Q needs to be assessed. The complexity of the retrieval method and subsequent manipulation of data preclude a precise estimate of the errors involved. The best that can be done is to compare independently derived fields, as we do here for the middle atmosphere of the southern hemisphere.

Isentropic maps of Q on the 850 K surface (near 10 mb) for 24 May 1979 are shown in Figs. 4(a) and 4(b). The LIMS and SSU fields are in broad agreement, though there are noticeable differences. A tongue of high Q in the LIMS field near 30°W has no couterpart in the SSU field. Generally, SSU maps of Q exhibit more longitudinal structure than do LIMS maps. Some of this structure could be real, being on a scale that could be revealed by the good horizontal resolution afforded by side scanning on the SSU instrument (see Clough et al., Figs. 2(a) and 10, for illustration). However, small-amplitude ripples, such as those in the top half of Fig. 4(b), are probably artefacts of the methods of observation and derivation of gridded fields.

A feature both maps have in common is a large-scale extrusion of high Q into low latitudes near 180°E, and a localised minimum in Q adjacent to it near 90°E. Such a pattern is characteristic of the early stages of 'wave breaking', a process that may lead to an irreversible exchange of air between high and low latitudes (see McIntyre and Palmer, 1984, for a detailed discussion of this concept). The ability to discern such behaviour from atmospheric data is crucial to a complete understanding of transport mechanisms (e.g. of ozone). Preliminary indications are that for the middle atmosphere of the southern hemisphere a blurred view of the process can be gained on some occasions for large scales of motion in a deep layer of the atmosphere (though quantitative details would be unreliable). Corroboration comes from the ozone mixing ratio on the 850 K surface derived from LIMS measurements for 24 May 1979 (Fig. 4(c)). There is a high degree of correlation between the LIMS fields of Q and ozone. Other authors have also found such a correlation between satellite-derived fields of Q and quasi-conservative constituents in the middle and lower stratosphere (e.g. Grose, 1984; Leovy et al. 1985).

3.5 Influence of different base levels on derived quantities

In principle, basic retrieved fields from satellites (temperature for LIMS; thickness for SSU) need be no less accurate in the southern hemisphere than they are in the northern hemisphere. Indeed the spatially uniform quality of the measurements is one of the main advantages of using satellite data in diagnostic studies. To calculate many quantities of dynamical interest, however, a field of geopotential height at a base level (usually in the lower stratosphere) is also needed. Herein lies the main shortcoming of derived quantities for the southern hemisphere: conventional observations of the troposphere and lower stratosphere (e.g. from radiosondes) are sparse. It is not our purpose here to judge the reliability of base level analyses made available by different meteorological centres. Rather, it is to illustrate the differences in derived quantities (zonal-mean wind, divergence of the Eliassen-Palm flux, Q) that are produced in the stratosphere when data from one instrument - in this case the SSU - are used in conjunction with various base-level analyses of geopotential height at 100 mb. SSU thicknesses were tied to base-level analyses provided by ECMWF, NMC and UKMO. Geostrophic winds were then calculated and used in computing E-P flux divergence and Q.

Three cross-sections of zonal-mean geostrophic wind on 8 September 1985 are shown in Fig. 5. At 100 mb, the three fields differ by up to nearly 10 ms^{-1} at high latitudes (the -10 contour near 80°S is present only in the NMC analysis), the impact of which is noticeable up to the middle stratosphere. At middle and low latitudes, however, there is good agreement between the fields. These findings are typical for September 1985.

Three cross-sections of the E-P flux divergence on 8 September 1985 are

shown in Fig. 6. Although the three fields all have divergence in the stratosphere at high latitudes and convergence at middle latitudes, there are significant differences. At high latitudes in the upper stratosphere, divergence with the ECMWF base is half as large as that with the others; while at 55°S there is a region of divergence with the NMC base but not with the others. Notice also that there are significant differences at high latitudes in the troposphere.

Three synoptic maps of Q on the 850 K isentropic surface on 24 September 1985 are shown in Fig. 7. The fields are generally in good agreement. This result is only to be expected since derivatives of the thickness field (a field the three maps have in common) contribute most to the value of Q. At low latitudes, however, horizontal gradients of the thickness field become small, and those of the geopotential-height field at the base level contribute proportionally more to the value of Q. Moreover, gradients of Q are small at low latitudes, so a small difference between base-level analyses can make a big difference to an isopleth's position. Thus although the tongue of locally high Q near 180°E appears on all three maps, it extends further westward for the ECMWF base.

Karoly (1987) has made a parallel study of the impact of base-level analyses on certain circulation statistics (including momentum and heat fluxes, Elaissen-Palm fluxes and their divergence) for the stratosphere of the southern hemisphere in September 1981. He finds, as we do, that the statistics that are most sensitive to the different base-level analyses are those that emphasize the shortest spatial scales through multiple differentiation of the geopotential-height field.

3.6 Base level fields

The three base-level fields of geopotential height used in our comparison above are shown in Fig. 8. Superficially, there is not much difference between them (though note the difference of about 200 metres between geopotential heights near the centre of the vortex in the NMC and ECMWF analyses). Two distinct troughs near 90°W and 180°W are present on all three maps; otherwise the flow is almost zonal. Slight difference in horizontal gradient may, however, be magnified when derived quantities are computed for the stratosphere.

Bigger differences are found in the temperature fields at 100 mb (not shown). Near the south pole on the day shown, temperatures from ECMWF are about 10 K colder than those from either NMC or UKMO, so geopotential heights at the next analysed level up (50 mb) are lower over the pole in the ECMWF analysis. The influence of this discrepancy is spread in the vertical by vertical differentiation to obtain E-P flux convergence and Q.

5. CONCLUDING REMARKS AND RECOMMENDATIONS

5.1 General comments

Overall, examination of the basic meteorological fields (temperatures, winds) derived from measurements by different satellites leads to similar conclusions to those reached in the PMP-1 comparison of data for the northern hemisphere. While there is usually qualitative agreement between the different sets of fields, substantial quantitative differences are evident. Differences in magnitude and gradient are apparent in the

temperature fields, which result in more pronounced differences in fields of derived winds, Ertel's potential vorticity, and (for the LIMS/SSU comparison especially) Eliassen-Palm flux divergence..

It is clear from our study that the fidelity of the base-level analysis is of great importance in calculating derived quantities for the middle atmosphere, especially in the southern hemisphere. This was demonstrated by using a single set of satellite data (from an SSU) with base-level analyses obtained from three meteorological centres (ECMWF, NMC, UKMO). The Eliassen-Palm flux divergence is particularly sensitive to the base-level analysis (though it can be more sensitive to the instrument used), as is Ertel's potential vorticity at low latitudes where horizontal gradients are weak (and most meridional transport by eddies takes place).

These findings are representative of the periods selected for the present study; they also emerged from the more extensive comparison of satellite data for the southern hemisphere made by participants in the Williamsburg workshop (see acknowledgements).

5.2 Recommendations

On the basis of the experience that we have gained from this study and from the PMP-1 and Williamsburg workshops, we feel it prudent to advise caution in drawing inferences, particularly quantitative ones, from meteorological fields derived from satellite data. Such counsel is certainly apt for the southern hemisphere where coverage of data from sources other than satellites is limited.

There are several techniques that may be used to evaluate the reliability of the information contained in the measurements:

(1) Independent data sets (derived from different instruments and base-level analyses) should, ideally, be used in parallel and examined for consistency.

(2) The temporal continuity of derived fields is often useful in highlighting problems with the data.

(3) Consistency between zonal-mean meridional velocities inferred separately from zonally averaged momentum and thermodynamic equations provides a powerful constraint (assuming unknown friction can be neglected).

(4) The conservation of potential vorticity over a period of a week or so in the middle stratosphere is an important objective check on the reliability of the analyses.

(5) A good correlation over short periods between some quasi-conservative chemical species (whose concentrations are measured directly) and Ertel's potential vorticity (a highly derived quantity) is persuasive evidence that the data have at least qualitative value.

A comparative appraisal of the procedures used to construct the different base-level analyses for the southern hemisphere would be of value to students of the middle atmosphere. Such a task is beyond the scope of the average user of the data; those who produce the analyses are best placed to assess them.

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FIGURE CAPTIONS

Fig. 1 Zonal-mean temperature (°C) for the southern hemisphere on 19 May 1979. (a) From LIMS, (b) from SSU.

Fig. 2 Zonal-mean geostrophic wind (m s^{-1}) for the southern hemisphere on 19 May 1979. (a) From LIMS, (b) from SSU.

Fig. 3 The convergence of the Eliassen-Palm flux, scaled to give the zonal force per unit mass due to eddies, for the southern hemisphere on 19 May 1979. It is the quantity denoted as D_F by Dunkerton et al. (1981). Units: 10^{-5} m s^{-2}. (a) From LIMS, (b) from SSU. Pecked lines indicate negative values (convergence).

Fig. 4 (a) LIMS and (b) SSU maps of moduluse of Ertel's potential vorticity (see main text for approximate form used) on the 850 K isentropic surface for the southern hemisphere on 24 May 1979. Units: 10^{-4} K m^2 kg^{-1} s^{-1}. (c) Ozone mixing ratio (ppmv) from LIMS on the 850 K surface on the same day.

Fig. 5 Zonal-mean geostrophic wind (m s^{-1}) for the southern hemisphere on 8 September 1985. Fields constructed using different base-level analyses of geopotential height at 100 mb: (a) ECMWF base level; (b) NMC base level; (c)UKMO base level.

Fig. 6 As for Fig. 5 but for convergence of Eliassen-Palm flux, scaled as in Fig. 3. Units: 10^{-5} m s^{-2}. Stippling indicates positive values (divergence).

Fig.7 Synoptic maps of modulus of Ertel's potential vorticity on the 850 K isentropic surface for the southern hemisphere on 24 September 1985. Units: 10^{-4} K m^2 kg^{-1} s^{-1}. Fields constructed using different base-level analyses of geopotential-height at 100 mb: (a) ECMWF base; (b) NMC base; (c) UKMO base.

Fig. 8 Base-level analyses of geopotential height (dam) at 100 mb for the southern hemisphere on 8 September 1985. They are derived independently at three meteorological centres: (a) ECMWF, (b) NMC and (c) UKMO.

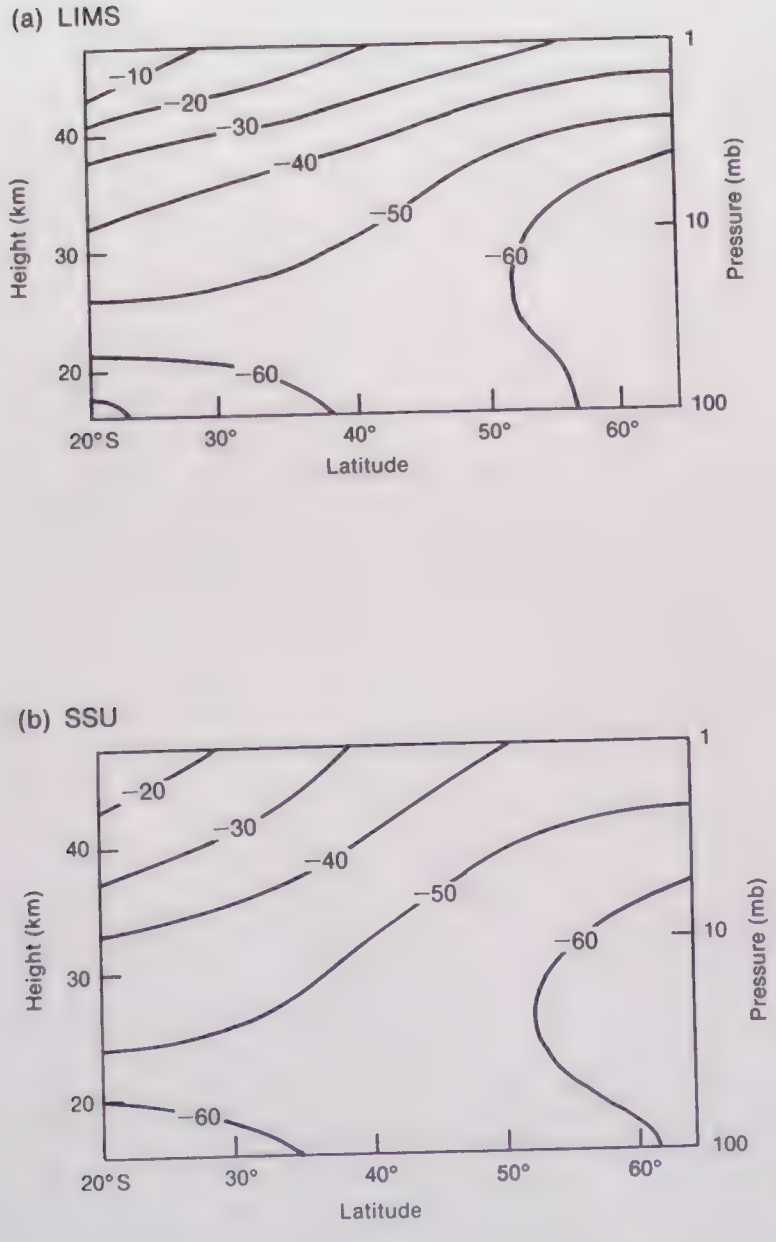
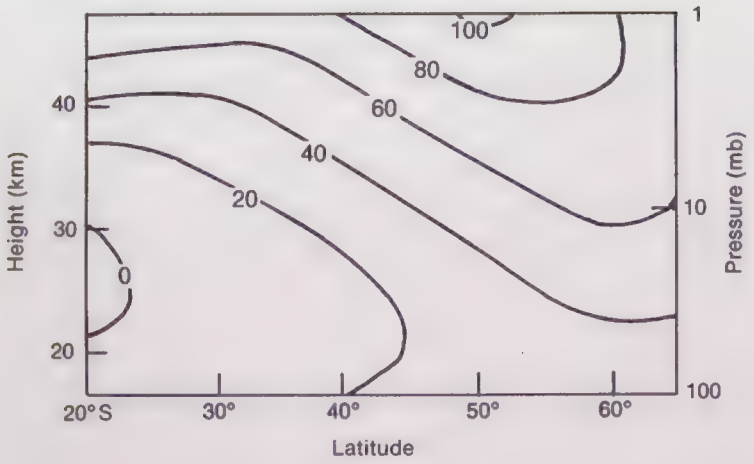

(a) LIMS
−10
−20
−30
−40
−50
−60
−60
40
30
20
Height (km)
1
10
100
Pressure (mb)
20°S
30°
40°
50°
60°
Latitude
(b) SSU
−20
−30
−40
−50
−60
−60
40
30
20
Height (km)
1
10
100
Pressure (mb)
20°S
30°
40°
50°
60°
Latitude

Fig. 1

(a) LIMS



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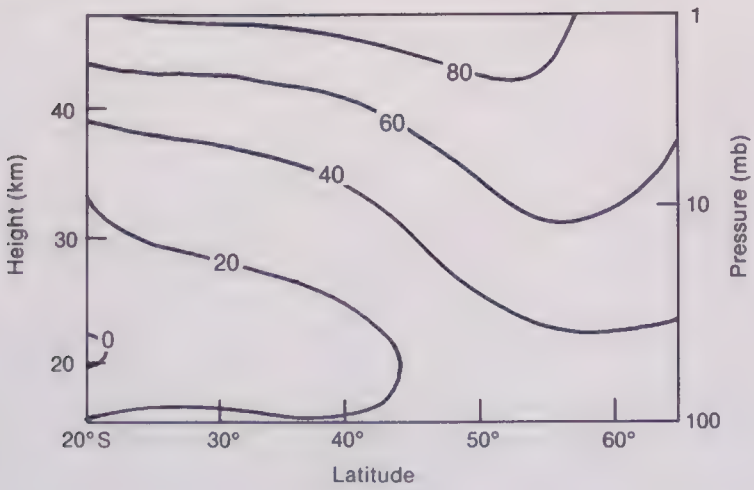
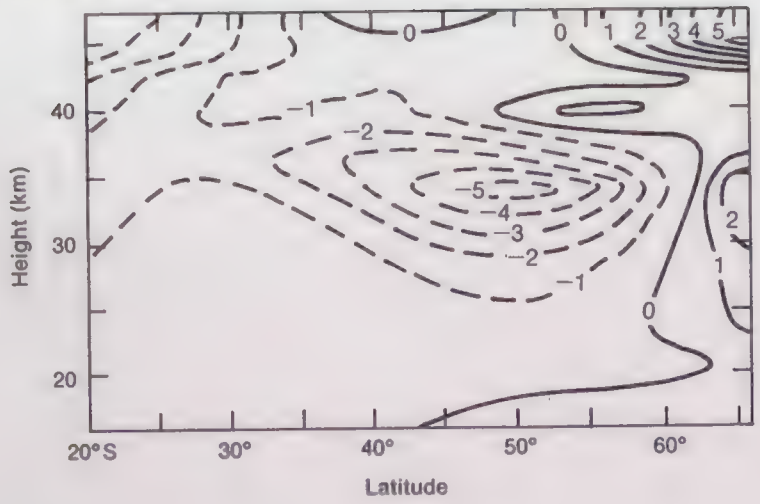


Fig. 2

(a) LIMS



(b) SSU

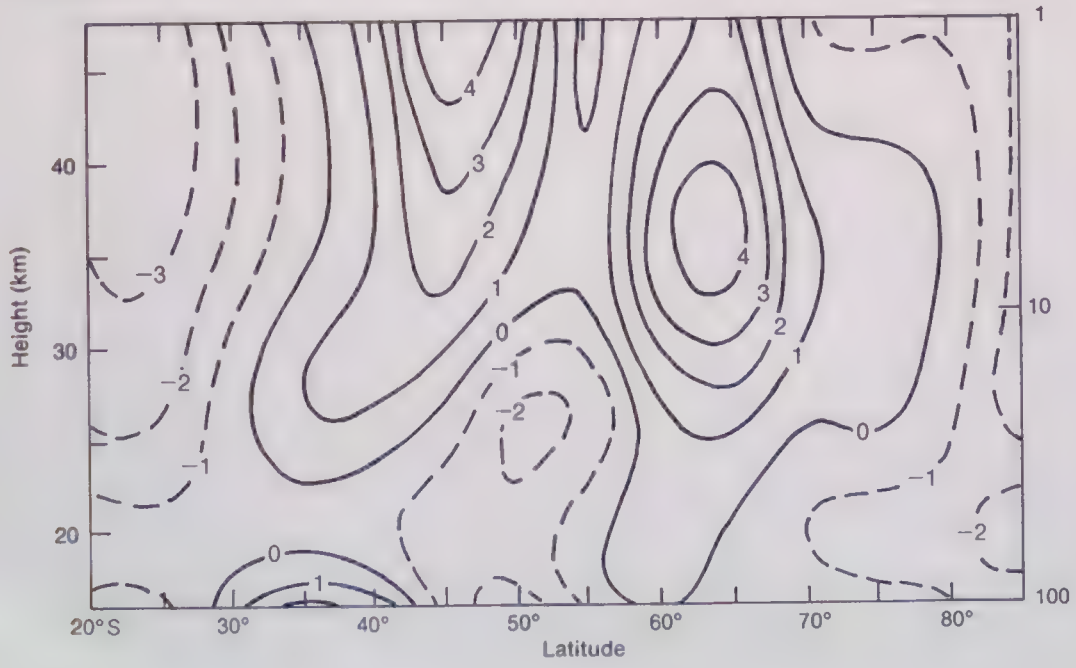
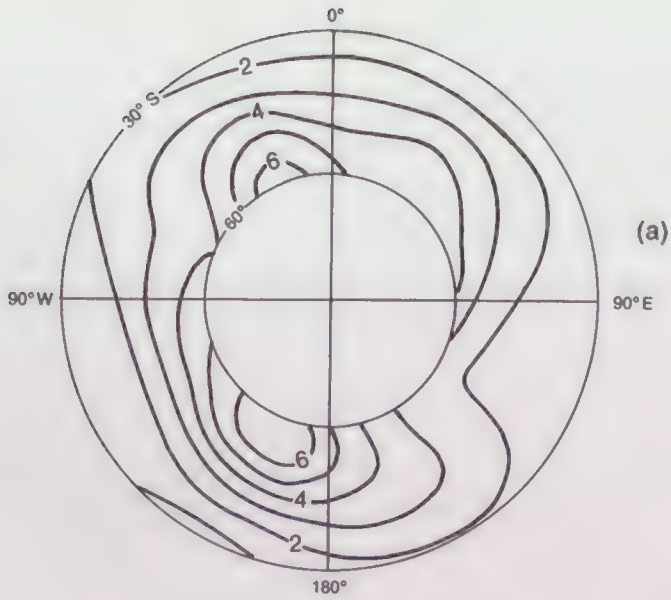
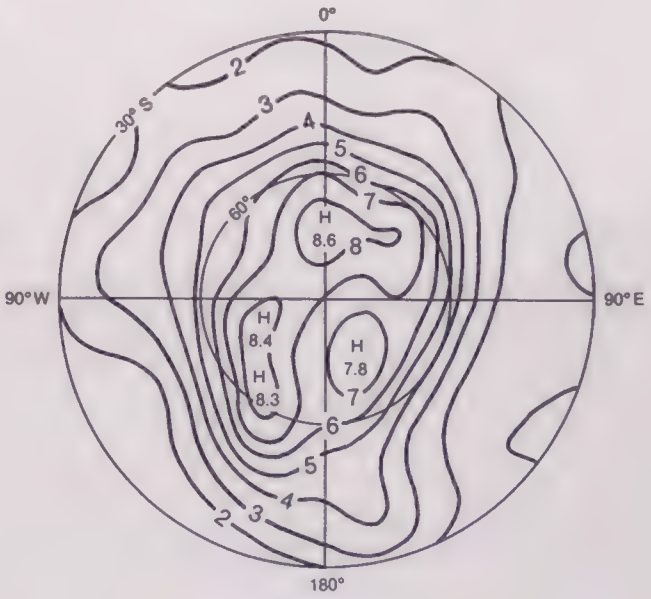


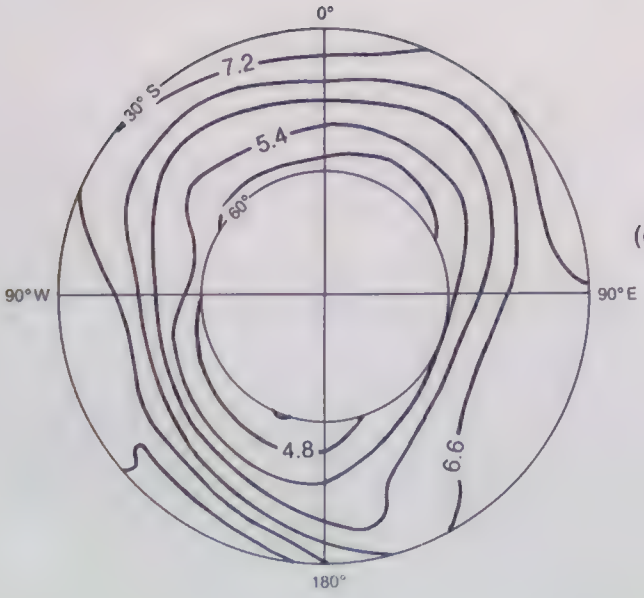
Fig. 3



(a) LIMS (potential vorticity)



(b) SSU (potential vorticity)



(c) LIMS (ozone)

Fig. 4

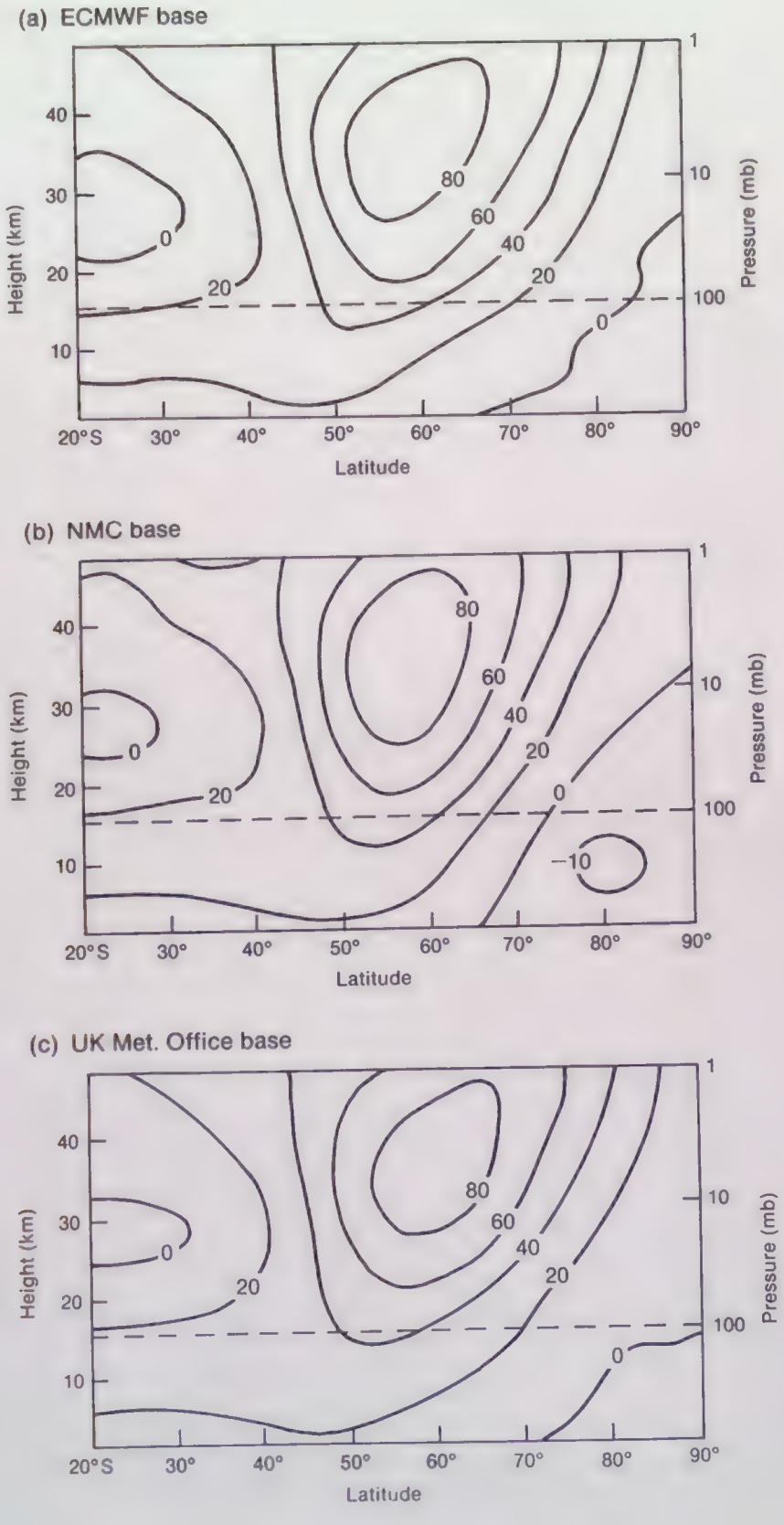

(a) ECMWF base
(b) NMC base
(c) UK Met. Office base
Height (km)
Pressure (mb)
Latitude
20°S
30°
40°
50°
60°
70°
80°
90°
1
10
100
0
20
40
60
80
−10

Fig. 5

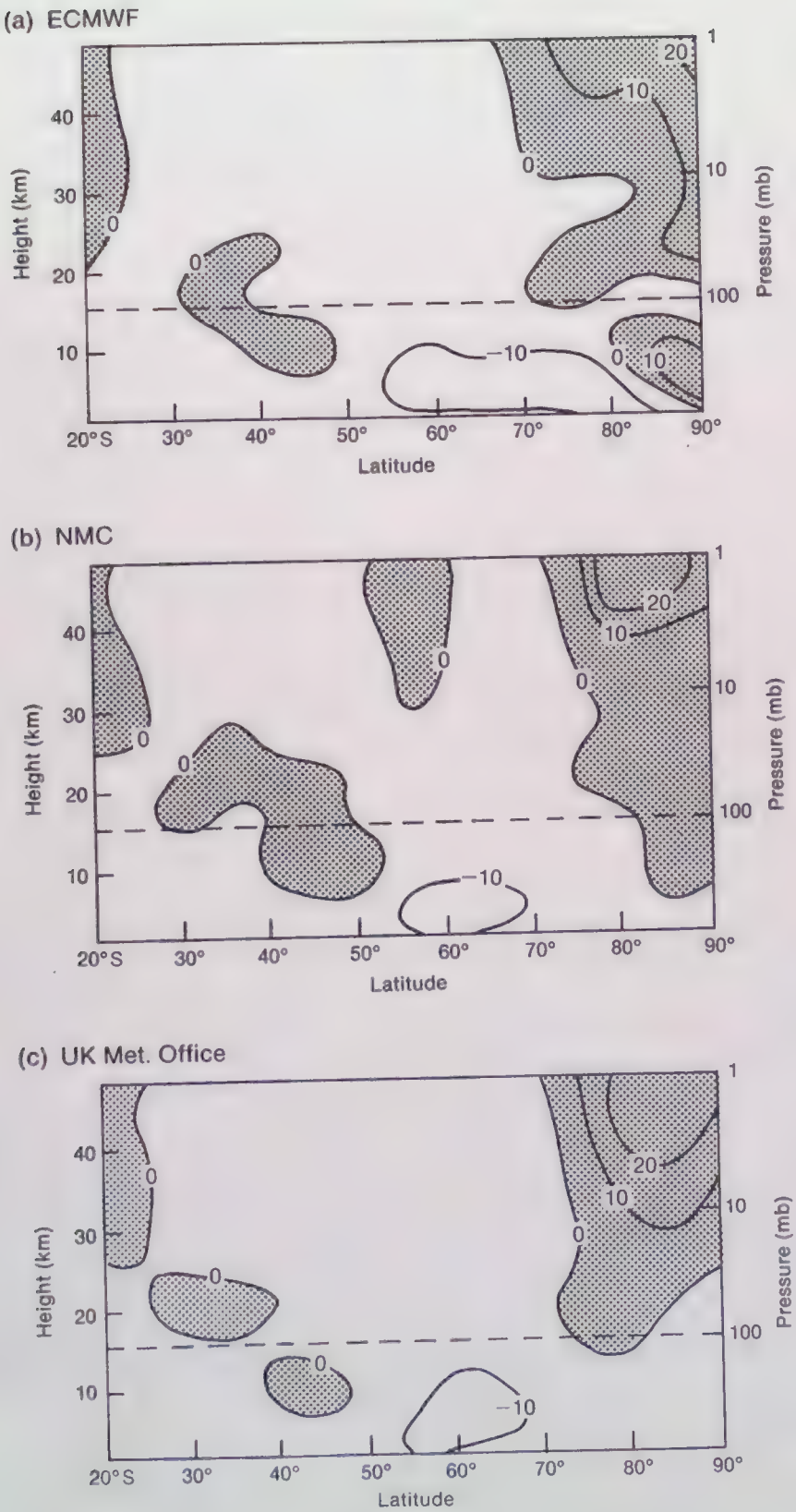
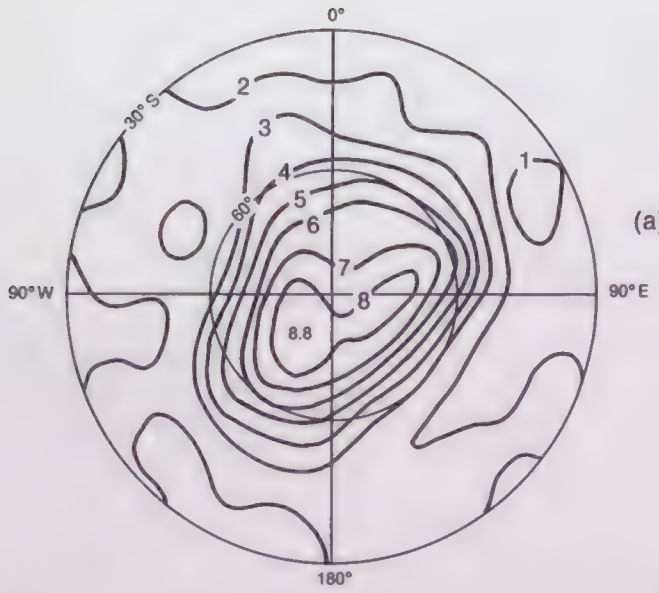
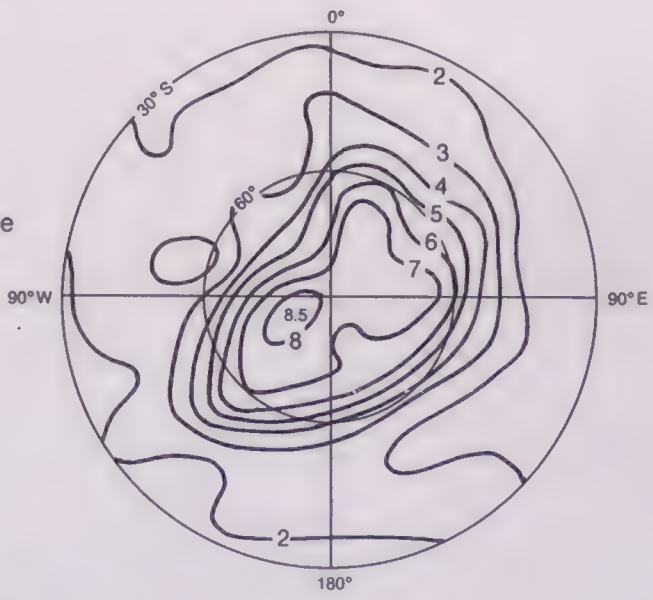

(a) ECMWF
Height (km)
Pressure (mb)
Latitude
20°S
30°
40°
50°
60°
70°
80°
90°
(b) NMC
Height (km)
Pressure (mb)
Latitude
(c) UK Met. Office
Height (km)
Pressure (mb)
Latitude

Fig. 6



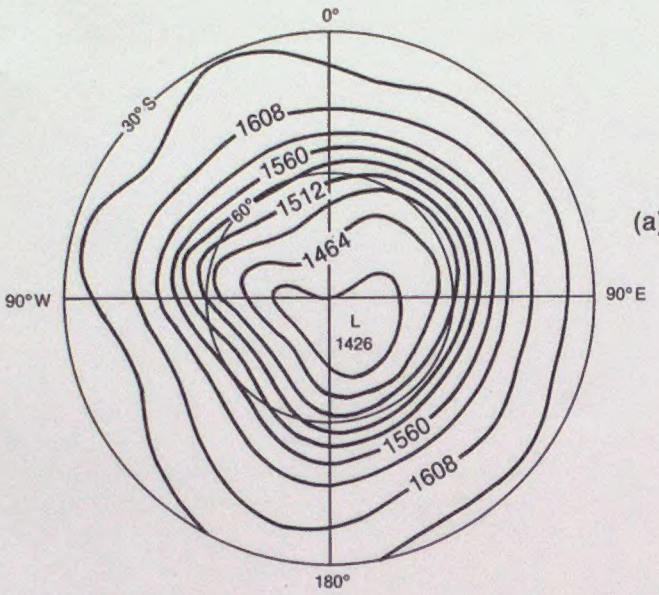
(a) ECMWF base



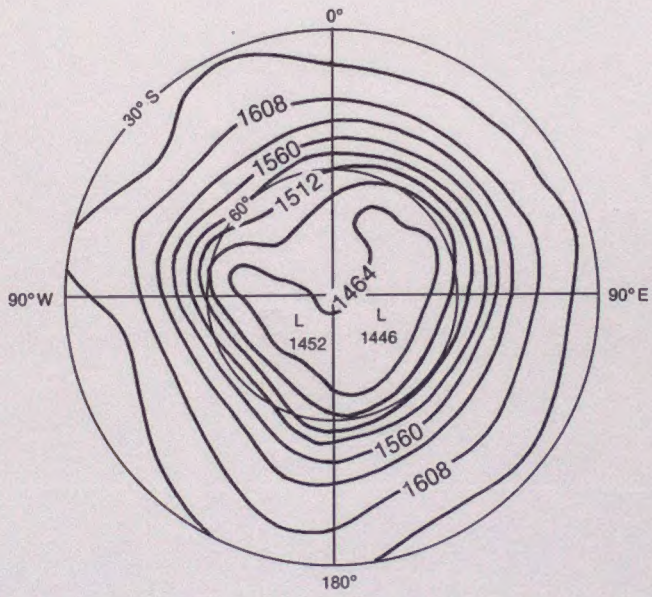
(b) NMC base

(c) UK Met. Office base

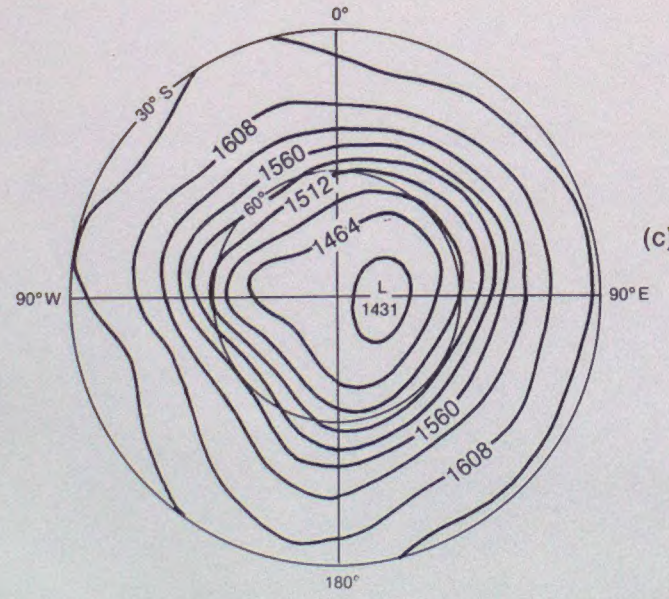
Fig. 7



(a) ECMWF



(b) NMC



(c) UK Met. Office

Fig. 8

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